Collider Signals of New Physics Beyond The Standard Model

A THESIS

submitted for the award of Ph.D. degree of

MOHANLAL SUKHADIA UNIVERSITY

in the

Faculty of Science

by

Pankaj Sharma

Under the Supervision of

Saurabh D. Rindani
Senior Professor
Theoretical Physics Division
Physical Research Laboratory
Ahmedabad, India

DEPARTMENT OF PHYSICS
MOHANLAL SUKHADIA UNIVERSITY
UDAIPUR
Year of submission: 2011

To

mummy, papa, munnu and manku

DECLARATION

*I **Mr. Pankaj Sharma**, S/o Mr. Tara Prakash Sharma, resident of 202, PRL Thaltej Hostel, Bodakdev, Ahmedabad 380009, hereby declare that the work incorporated in the present thesis entitled, **"Collider signals of new physics beyond the Standard Model"** is my own and original. This work (in part or in full) has not been submitted to any University for the award of a Degree or a Diploma. I solely own the responsibility for the originality of the entire document.*

Date :

(Pankaj Sharma)

CERTIFICATE

I feel great pleasure in certifying that the thesis entitled, **"Collider signals of new physics beyond the Standard Model"** embodies a record of the results of investigations carried out by Mr. Pankaj Sharma under my guidance.

He has completed the following requirements as per Ph.D. regulations of the University.

(a) Course work as per the university rules.

(b) Residential requirements of the university.

(c) Presented his work in the departmental committee.

(d) Published minimum of two research papers in a referred research journal.

I am satisfied with the analysis of data, interpretation of results and conclusions drawn.

I recommend the submission of thesis.

Date :

Saurabh D. Rindani
Senior Professor
(Thesis Supervisor)

Countersigned by
Head of the Department

Acknowledgements

It is a great pleasure to acknowledge those people who have helped me grow into the physicist I am today. First and foremost is my thesis supervisor, Prof. Saurabh D. Rindani, who has always encouraged me to learn invaluable techniques and skills, and shared with me many of his interesting ideas on which to pursue research. Dr. Namit Mahajan who has always provided invaluable guidance in research and always encouraged to pursue challenging problems. Apart from academics, he has been a great motivator and support during my stay here at PRL.

I would like to thank all my collaborators Prof. Katri Huitu, Prof. Rohini Godbole, Prof. M. Mullheitner, Dr. Rui Santos, Dr. Ritesh K. Singh, Dr. Kumar Rao, Dr. Santosh K. Rai, Dr. Sudhanshu Biswal, Christian Hangst, Miguel Won and Ketan Patel for providing opportunities to work with them. Working with them was really fun and interesting. In particular, working with Ketan and Sudhansu was really inspiring and sharing ideas with them provided great insight. I am also really thankful to Dr. Rui Santos for providing me a visit to HEP Group of Univ. of Southampton and for some really interesting discussions.

I would also like to acknowledge the support of all my colleagues at PRL with whom I spent five important years of my life, in particular, JRF06 batch. I am really grateful to Subimal da and Suman for giving me early lessons in Linux and patiently helping me. I thank Arvind, Ashwini, Debagnik, Vineet and Vimal for all the happy times together at Thaltej Hostel. The memories of the joyful time I spent at Tulip with Anand, Rabiul and Vimal are unforgettable. The company of Bhavik, T.K. Jha, Bhaswar, Ashok, Amzad, Sreekanth, Gyan and Alok at PRL main Hostel had been enjoyable. I also cherish the time spent with my younger colleagues (JRF09 and JRF10) at Thaltej Hostel. In particular, I cannot forget the taste of delicious food cooked by Yashpal and Naveen. Also, the time spent with them at Hospital after the Nal-Sarovar accident.

I am also grateful to PRL administration for all the support provided to me here. Specifically, I would like to acknowledge the support of Jigar Bhai, Parul Madam, Ghanshayam Bhai, Ranganathan sir (from Medical cell), Senthil bhai, who have been highly efficient.

Last but not the least, I would like to thank my parents, my younger brother Anant, and Shivani for their encouragement, love and support.

Pankaj Sharma

Abstract

The Standard Model (SM) has been extremely successful in explaining the fundamental interactions among elementary particles. However, the electroweak symmetry breaking (EWSB) sector of the SM remains untested yet as its central pillar, known as the Higgs boson, has not been discovered so far. That is why the most important goal of the current and future colliders like the Large Hadron Collider (LHC) at CERN and the International Linear Collider (ILC) is to discover the Higgs boson and study its properties with great precision so as to ascertain it to be the SM Higgs as different alternate scenarios beyond the SM (BSM) e.g., Minimal Supersymmetric Standard Model (MSSM), Two Higgs Doublet Model (THDM) etc. allow for a number of Higgs particles. Also, the top quark, because of its large mass (close to EWSB scale), is considered to play an important role in the probe of EWSB. In this thesis, we study Higgs boson and top quark couplings in various new physics (NP) scenarios and at different colliders to probe the EWSB utilizing the polarization of the final state top quark at the LHC and the polarization of the initial beams at the ILC.

In the case of the ILC, we study anomalous ZZH and γZH couplings in the process $e^+e^- \to ZH$ with polarized initial beams. We consider both electron and positron beams to be polarized simultaneously. Our main emphasis in this work is to obtain simultaneous limits on the anomalous couplings to the extent possible making use of combination of observables and/or polarizations. We study angular distributions of the Z using both longitudinally as well as transversely polarized beams and construct various asymmetries. We also study the angular correlations of the charged leptons coming from Z decay. Using the momenta of the charged leptons, we construct various correlations having definite CP and T transformation properties. We find that the longitudinal polarization helps to enhance the sensitivities of the couplings relative to the unpolarized case. The most remarkable result from the study of transverse polarization is that it helps to probe a specific coupling $\mathrm{Im}a_\gamma$ which is inaccessible in the distributions with longitudinally polarized as well as unpolarized beams.

In the context of the LHC, we focus on the study of NP involved in single-top production. First we study the single-top production in association with a W^- boson to study the sensitivity of the LHC to anomalous tbW couplings. Here we also consider the possibility of CP violation. Then we study single-top production in association with a charged Higgs in THDM of type II and probe the parameters

of the model at the LHC. In these studies, we utilize polarization of the final state top quarks since different NP scenarios give different predictions for top polarization. As a measure of top polarization, we look at various laboratory frame distributions of its decay products, viz., lepton angular and energy distributions and b-quark angular distributions, without requiring reconstruction of the rest frame of the top. In the charged Higgs case, we only study charged lepton angular distributions as they have been proven to be independent of any NP involved in top-decay and hence are the pure probes of parameters of THDM contributing only in the production. We construct certain asymmetries to study the sensitivity of these distributions to the NP involved in the single-top production. We find that these asymmetries are sensitive probes of the NP involved in the single-top production.

List of Publications

A. Papers related to thesis

1. **“Angular distributions as a probe of anomalous ZZH and gammaZH interactions at a linear collider with polarized beams”**
   S. D. Rindani and P. Sharma
   Phys. Rev. D **79**, 075007 (2009) [arXiv:0901.2821 [hep-ph]]

2. **“Decay-lepton correlations as probes of anomalous ZZH and gammaZH interactions in $e^+e^- \to ZH$ with polarized beams”**
   S. D. Rindani and P. Sharma
   Phys. Lett. B **693**, 134 (2010) [arXiv:1001.4931 [hep-ph]]

3. **“Probing anomalous tbW couplings in single-top production using top polarization at the Large Hadron Collider”**
   S. D. Rindani and P. Sharma
   arXiv:1107.2597 [hep-ph]

4. **“CP violation in tbW couplings at the LHC”**
   S. D. Rindani and P. Sharma
   arXiv:1108.4165 [hep-ph]

5. **“Probing top charged-Higgs production using top polarization at the Large Hadron Collider”**
   K. Huitu, S. K. Rai, K. Rao, S. D. Rindani and P. Sharma
   JHEP **1104**, 026 (2011) [arXiv:1012.0527 [hep-ph]]

B. Other Publications

1. **“Model-independent analysis of Higgs spin and CP properties in the process $e^+e^- \to t\bar{t}\Phi$”**
   R. M. Godbole, C. Hangst, M. Muhlleitner, S. D. Rindani and P. Sharma
   Eur. Phys. J. C **71**, 1681 (2011) [arXiv:1103.5404 [hep-ph]]

2. **“Forward-backward asymmetry in top quark production from light colored scalars in SO(10) model”**

K. M. Patel and P. Sharma
JHEP **1104**, 085 (2011) [arXiv:1102.4736 [hep-ph]]

C. Conference proceedings

1. **"Working group report: Physics at the Large Hadron Collider"**
   D. K. Ghosh *et al.*,
   Proceedings of WHEPP XI held at PRL on Jan 2-12, 2010,
   Pramana **76**, 707 (2011)

2. **"Probing anomalous ZZH and gammaZH interactions at an e+e- linear collider using polarized beams"**
   S. D. Rindani and P. Sharma
   arXiv:1007.3185 [hep-ph]
   To appear in the proceedings of International Linear Collider Workshop 2010 (LCWS10 & ILC10), Beijing, China, 26-30 Mar 2010

3. **"Constraining anomalous ZZH and gamma ZH interactions in the process $e^+e^- \to HZ$ at a linear collider with polarized beams "**
   S. D. Rindani and P. Sharma
   Proceedings of the XVIII DAE-BRNS (High Energy Physics Symposium),13-18 Dec 2008, Volume 18 (2008)

Abbreviations

BR	Branching Ratio
BSM	Beyond Standard Model
CKM	Cabbibo Kobayashi Maskawa
CLIC	Compact Linear Collider
CL	Confidence Level
cm	centre of mass
ev	electron-volts
EW	ElectroWeak
EWSB	ElectroWeak Symmetry Breaking
fb	femto barn
GUT	Grand Unification Theory
GeV	Giga Electron Volt
ILC	International Linear Collider
LC	Linear Collider
LEP	Large Electron-Positron Collider
LHC	Large Hadron Collider
LO	Leading Order
MeV	Mega Electron Volt
MSSM	Minimal Supersymmetric Standard Model
NLO	Next-to-Leading Order
NLL	Next-to-Leading Log
NP	New Physics
NWA	Narrow-Width Approximation
PDF	Parton-Distribution Function
pb	pico barn
RG	Renormalization Group
RGE	Renormalization-Group Evolution
SLAC	Stanford Linear Accelerator
SLC	SLAC Linear Collider
SLD	SLAC Large Detector
SM	Standard Model

SUSY	Supersymmetry
TeV	Tera Electron Volt
THDM	Two Higgs Doublet Model
QCD	Quantum Chromodynamics
QED	Quantum Electrodynamics
vev	vacuum expectation value

Contents